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13. ABSTRACT *(Maximum 200 words)*

The report contains information on ARPA ASSERT AFORSR #F49620-94-1-0167, Single wafer plasma reactor simulator. This information includes details of the objectives of the ASSERT project to optimize single wafer design and operation, and focuses on a protocol known as Programmed Rate Chemical Vapor Deposition. Justification for deviation from the original proposal, verification of time savings using this protocol, and transactions communicating and disseminating this protocol to interested parties are discussed.

Sections in the report include Accomplishments/New Findings (e.g., the time savings verification), personnel supported, associated personnel, publications, transactions, and interactions explaining the work are also included, as well as future work to which this research could be applied.

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SINGLE WAFER PLASMA REACTOR SIMULATOR

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FINAL PROGRESS REPORT
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GRANT NO. F49620-94-1-0167

OBJECTIVES: To develop methods to optimize single wafer reactor design and operation. In the work supported by this grant, we have focused on experimental verification of a protocol for chemical vapor deposition known as programmed rate CVD (PRCVD). PRCVD takes advantage of process conditions [1] to produce higher throughput than conventional constant rate chemical vapor deposition (CRCVD) methods, while maintaining or improving film properties.

As was explained in the previous Progress Reports, this work differs from the original proposal for a single wafer reactor plasma simulator. However, it is in keeping with the goal of developing improved processing techniques through simulation and experimental verification, as laid out in the *National Technology Roadmap for Semiconductors* [2].

STATUS OF EFFORT: We have verified that PRCVD can be used to deposit tungsten at a much higher average rate than CRCVD processes, while maintaining acceptable or superior film properties. K.M. Tracy, the student previously supported by this ASERT, and S. Bolnedi experimentally verified the PRCVD protocol [3, 4, 5] that Cale and co-workers developed [1].

J. J. Kristof, the student most recently supported by the Grant, is continuing work to implement a control protocol based on optimal control modeling [6, 7, 8]. Talks which explain this model and its application to PRCVD process were presented to semiconductor industry personnel at the Semiconductor Research Corporation Technology Transfer Course on EVOLVE 5.0 [9] and at the International Conference on Metallurigical Coatings and Thin Films (ICMCTF 97) [10].

Papers that explain the model, as well as poster sessions that enabled and will enable interaction with interested parties, were [11] and will be [12] presented at the 1997 VLSI Multilevel Interconnection Conference, June 10-12, 1997 and at the 14th International CVD Symposium of the Electrochemical Society, Paris, France, in September, 1997. Results from the OPRCVD work will be published in Kristof's Masters Thesis in September, 1997.

Future work will extend PRCVD methods to control amorphous films of silicon dioxide and take advantage of the differences in activation energies for nucleation and growth of many films; e.g. aluminum and copper.

ACCOMPLISHMENTS/NEW FINDINGS: Experimentally verified PRCVD protocol as a viable process for tungsten that can improve wafer throughput for SWR by 50 - 90 %, depending on operating conditions. Developing a method to use optimal control models to improve wafer throughput for the experimental equipment.

Related work:

1."Single Wafer Plasma Reactor Simulator", ARPA (AASERT), 3/94-3/97, $89,000.

2. "Mathematical Modeling for Simulation and Control of Semiconductor Processes", DARPA, 10/92-9/95, $693,000. (P. Crouch is P.I.)

3. "Process Development Tools for Single Wafer Reactors", and "Process Development Tools for Single Wafer LPCVD Reactors: Step Coverage Prediction", Semiconductor Research Corporation, 1/90-1/97, $975,500. (G. B. Raupp is Co-P.I.)

4. Using Films Deposited in Features to Establish Kinetic and Transport Models", NSF, 2/94-1/97, $214,000. (G. B. Raupp is Co-P.I.)

5. Programmed Rate Chemical Vapor Deposition", NSF, 3/90-3/94, $255,059. (G. B. Raupp is Co-P.I.)

PERSONNEL SUPPORTED:

Kathryn M. Tracy	11/94 - 12/95
John J. Kristof	05/96 - 05/97.

ASSOCIATED PERSONNEL:

T. S. Cale, ASU	L. J. Song, ASU
K. S. Tsakalis, ASU	V. Mahadev, ASU

PUBLICATIONS:

Directly Supported By This AASERT:

"Programmed Rate Chemical Vapor Deposition of Tungsten," J. J. Kristof, L. J. Song, K. S. Tsakalis, T. S. Cale, abstract accepted for International Conference on Metallurigical Coatings and Thin Films, ICMCTF 97.

"Programmed Rate Chemical Vapor Deposition: Blanket Tungsten Film Characterization", Master's Thesis by K.M. Tracy, 1996.

"Blanket Tungsten Film Deposition Using Programmed Rate CVD", K. M. Tracy, S. Bolnedi, G. J. Leusink and T. S. Cale, in Advanced Metalization and Interconnect Systems for ULSI Applications in 1995, MRS, p. 563.

"Programmed Rate Chemical Vapor Deposition of Blanket Tungsten Thin Films", K. M. Tracy, S. Bolnedi, T. S. Cale, in Proceedings of the 12th International VLSI Multilevel Interconnection Conference, T. Wade, ed., VMIC, 1995, p.643.

Previous work on this topic:

"Reactor Scale and Feature Scale Simulations of Programmed Rate CVD", J.-H. Park and T. S. Cale, in "Proceedings of the First International Conference on Rapid Thermal Processing", 1993, p. 393.

"Programmed Rate Processing to Increase Throughput in LPCVD", T. S. Cale, M. K. Jain and G. B. Raupp, J. Electrochem. Soc. 137(5), 1526 (1990).

"Programmed Rate Processing to Increase Single Wafer Reactor Throughput in Blanket Tungsten LPCVD", T. S. Cale, M. K. Jain and G. B. Raupp, in Tungsten and Other Advanced Metals for ULSI/VLSI Applications V, S. S. Wong and S. Furukawa, eds., Materials Research Society, 1990, p. 179.

"The Inherently Transient Nature of Deposition Processes", T. S. Cale, G. B. Raupp, J. H. Park, M. K. Jain and B. R. Rogers, in First International Conference on Transport Phenomena in Processing, S. Guceri, ed., Technomic Publishing Company, 1993, p. 127.

"Impacts of Temperature and Reactant Flow Rate Transients on LPCVD Tungsten Silicide Film Properties", T. S. Cale, G. B. Raupp and J. H. Park, in Rapid Thermal and Integrated Processing, MRS Symp. Proc. ,Vol. 224, MRS, 1991, p. 171.

"A Methodology for Rapidly Optimizing Step Coverage for LPCVD Tungsten", S. Bolnedi, D. Wang, G. B. Raupp and T. S. Cale, in Advanced Metalization and Interconnect Systems for ULSI Applications in 1995, MRS, in press.

(Invited) "Conformality and Composition of Films Deposited at Low Pressures", T. S. Cale, in Modeling and Simulation of Thin-Film Processing, D. J. Srolovitz, C. A. Volkert, M. J. Fluss and R. J. Kee, eds., MRS Symp. Proc., Vol. 389, MRS, 1995, p. 95.

(Invited) "The Impact of Gas Phase and Surface Chemical Reactions on Step Coverage in LPCVD", G. B. Raupp and T. S. Cale, Invited paper in Gas Phase and Surface Chemistry in Electronic Materials Processing, T. J. Mountziaris, G. R. Paz-Pujalt, F. T. J. Smith, and P. R. Westmorland, eds., MRS Symp. Proc., Vol. 334, MRS, 1994, p. 471.

Publications that form the basis for the continuing work:

"A Simple Adaptive Optimization Algorithm for the Tungsten LPCVD Process", T. S. Cale, P. E. Crouch, S. Shen and K. S. Tsakalis, in Proceedings of the 1995 American Control Conference, American Control Council, IEEE, 1995, p. 1294.

"Increasing Throughput in Low Pressure Chemical Vapor Deposition: An Optimal Control Approach", T. S. Cale, P. E. Crouch, L. Song and K. S. Tsakalis, in Proceedings of the 1995 American Control Conference, American Control Council, IEEE, 1995, p. 1289.

"Optimal Control Processing to Increase Single Wafer Reactor Throughput in LPCVD", P. E. Crouch, L. Song, K. S. Tsakalis and T. S. Cale, in Proceedings of the Fourth IEEE/UCS/SEMI International Symposium on Semiconductor Manufacturing, IEEE, 1995, p. 233.

"Optimal Control for LPCVD", T. S. Cale, P. E. Crouch, L. Song and K. S. Tsakalis, in Proceedings of the Symposium on Process Control, Diagnostics and Modeling in Semiconductor Manufacturing, M. Meyyappan, D. J. Economou and S. W. Butler, eds., Electrochemical Society, proceedings volume 95-2, 1995, p. 97.

"Run-to-Run Adaptive Optimization of a Tungsten Silicide LPCVD Process", T. S. Cale, P. E. Crouch, S. Shen and K. S. Tsakalis, in Proceedings of the 34th Conference on Decision and Control, IEEE, 1995, p. 2474.

INTERACTIONS/TRANSITIONS:

Transitions: We have verified that PRCVD can be used to deposit tungsten processes while maintaining acceptable film properties. This work, if applied by industry, will significantly decrease processing time for tungsten metallization. At the ICMCTF and VMIC presentations there was considerable industry interest in the lower fluorine incorporation shown by the PRCVD process.

Further research may broaden the time savings achieved from PRCVD to silicon dioxide and aluminum films. It is our regret that the funding agency, AFOSR, did not deem it fit to grant the no-cost extension for a longer period of time, as current research is showing promising results. We were, however, thankful for the additional time that was allowed, as it enabled the completion of experiments that were in-progress at the time the contract officially ended.

Interactions:

"PRCVD of Tungsten as an Application of EVOLVE 5.0," J. J. Kristof, Semiconductor Research Corporation Technology Transfer Course on EVOLVE 5.0, Arizona State University, Mar 13-14, 1997.

"Programmed Rate Chemical Vapor Deposition of Tungsten," J. J. Kristof, L.J. Song, K.S. Tsakalis, and T. S. Cale, at the 24th International Conference on Metallurigical Coatings and Thin Films (ICMCTF 97), Session H1.07, on April 21-25, 1997.

"Optimally Controlled Programmed Rate Deposition of Tungsten," J. J. Kristof, L.J. Song, K.S. Tsakalis, and T. S. Cale, in Proceedings of the 14th International VLSI Multilevel Interconnection Conference, T. Wade, ed., VMIC, 1997, p.207.

"Programmed Rate And Optimal Control Chemical Vapor Deposition Of Tungsten," J. J. Kristof, L.J. Song, K.S. Tsakalis, and T. S. Cale, accepted for the 14th International CVD Symposium of the Electrochemical Society, Paris, France, September, 1997.

"Programmed Rate Chemical Vapor Deposition Of Tungsten," J. J. Kristof, L. J. Song, K. S. Tsakalis, K. M. Tracy, G. J. Leusink, and T. S. Cale, Poster Session for Semiconductor Research Corporation Techcon, Phoenix, AZ, September 12-14, 1996.

"Programmed Rate Chemical Vapor Deposition Of Tungsten," J. J. Kristof, L. J. Song, K. S. . Tsakalis, K. M. Tracy, G. J. Leusink, and T. S. Cale, Poster Session for Advanced Metalization and Interconnect Systems for ULSI Applications in 1996, Boston, MA, October 1-3, 1996.

"Programmed Rate LPCVD: Improved Throughput for Single Wafer Reactors," K. M. Tracy, L.J. Song, G. J. Leusink and T. S. Cale, J. J. Kristof, K. T. Tsakalis, Poster

Session for the Phoenix Chapter of the American Vacuum Society Spring Meeting, May 14, 1996.

"Programmed Rate LPCVD: Improved Throughput for Single Wafer Reactors," K. M. Tracy, L.J. Song, G. J. Leusink and T. S. Cale, J. J. Kristof, K. T. Tsakalis, Poster Session session for the Phoenix Chapter of the American Vacuum Society Spring Meeting, May 14, 1996.

"Programmed Rate LPCVD: Improved Throughput for Single Wafer Reactors", K. M. Tracy, S. Bolnedi, G. J. Leusink and T. S. Cale, presented during the International Conference on Metuallurgical Coatings and Thin Films, San Diego, CA, Apr. 22-26, 1996.

"Topography Evolution And Applications," T. S. Cale, presented during the IMA (Institute for Mathematics and its Applications) Workshop, Initiatives in Material Science, Jan. 24-26, 1996.

"PRCVD Blanket Tungsten Deposition", K. M. Tracy, S. Bolnedi, G. J. Leusink and T. S. Cale, presented during the 42nd National AVS Meeting, Minneapolis, MN, Oct. 16-20, 1995.

"Blanket Tungsten Film Deposition Using Programmed Rate CVD", K. M. Tracy, S. Bolnedi, G. J. Leusink and T. S. Cale, presented during Advanced Metalization and Interconnect Systems for ULSI Applications, Portland, OR, Oct. 3-5, 1995.

"Programmed Rate Chemical Vapor Deposition", T. S. Cale, B. R. Rogers, K. Tracy, P. E. Crouch, K. Tsakalis, S. Shen and L. Song, presented during the NATO ASI on Advances in Rapid Thermal and Integrated Processing, Maratea, Italy, July 3-14, 1995.

"Reactor Scale and Feature Scale Simulations of Programmed Rate CVD", J.-H. Park and T. S. Cale, presented at the First International RTP Conference, Phoenix, AZ, Sept. 7-9, 1993

"A Methodology for Rapidly Optimizing Step Coverage for LPCVD Tungsten", S. Bolnedi, D. Wang, G. B. Raupp and T. S. Cale, presented during Advanced Metalization and Interconnect Systems for ULSI Applications, Portland, OR, Oct. 3-5, 1995.

"Optimal Control for LPCVD Processes", P. E. Crouch, T. S. Cale, S. Shen, L. Song and K. S. Tsakalis, presented during the SEMATECH AEC/APC Workshop VII, New Orleans, LA, November, 5-8, 1995.

"Run-to-Run Adaptive Optimization of a Tungsten Silicide LPCVD Process", T. S. Cale, P. E. Crouch, S. Shen and K. Tsakalis, presented during the in 34th Conference on Decision and Control, New Orleans, LA, Dec. 13-15, 1995.

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"Optimal Control for LPCVD", T. S. Cale, P. E. Crouch, L. Song and K. S. Tsakalis, presented during the 187-th Meeting of the Electrochemical Society, Reno, NV, May 21-26, 1995.

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES: None
HONORS/AWARDS: None

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1. T. S. Cale, M.K. Jain and G.B. Raupp, J. Electrochem. Soc., **137**(5), 1990, p. 1526.

2. The National Technology Roadmap for Semiconductors, SIA, 1994, pp 74, 94, 162.

3. K. M. Tracy, Master's Thesis, Arizona State University, 1996.

4. K. M. Tracy, S. Bolnedi, G. J. Leusink and T. S. Cale, in Advanced Metalization and Interconnect Systems for ULSI Applications in 1995, MRS, p. 563.

5. K. M. Tracy, S. Bolnedi, T. S. Cale, in Proceedings of the 12th International VLSI Multilevel Interconnection Conference, T. Wade, ed., VMIC, 1995, p.643.

6. T.S. Cale, P. E. Crouch, L. J. Song, and K. S. Tsakalis, in Proceedings of the Symposium on Process Control, Diagnostics, and Modeling in Semiconductor Manufacturing, ECS, 1994, p. 97.

7. T. S. Cale, P.E. Crouch, L.J. Song, and K.S. Tsakalis, J. Electrochem. Soc., submitted for publication.

8. T. S. Cale, P. E. Crouch, L. Song and K. S. Tsakalis, in Proceedings of the 1995 American Control Conference, American Control Council, IEEE, 1995, p. 1289.

9. J. J. Kristof, "PRCVD of Tungsten as an Application of EVOLVE 5.0," Semiconductor Research Corporation Technology Transfer Course on EVOLVE 5.0, Arizona State University, Mar 13-14, 1997.

10. J. J. Kristof, L.J. Song, K.S. Tsakalis, and T. S. Cale, at the 24th International Conference on Metallurigical Coatings and Thin Films (ICMCTF 97), Session H1.07, on April 21-25, 1997.

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12. J. J. Kristof, L.J. Song, K.S. Tsakalis, and T. S. Cale, accepted for the 14th International CVD Symposium of the Electrochemical Society, Paris, France, September, 1997.